Equivalence-First Physics: Univalent Relational Dynamics, Category Theory, Homotopy Type Theory, and the Emergence of Reality from Coherent Relations

Douglas C. Youvan

doug@youvan.com www.youvan.com www.youvan.ai June 18, 2026

In conventional physics we begin with states: a particle with position and momentum, a field with values spread through space and time, or a quantum system described by a vector or wave function. Dynamical laws then tell us how these states change, while equivalences—gauge transformations, coordinate re-labelings, or symmetry operations—are introduced afterward to explain why different mathematical descriptions can represent the same physical situation. This paper reverses that order. It proposes that physical reality is fundamentally relational: what counts as the same entity is determined by the coherent, structure-preserving transformations that connect one local presentation to another. Drawing on category theory, in which objects are understood through the processes and relations linking them, and on homotopy type theory, in which identity itself takes the form of a path that can be continuously deformed at higher levels, the framework treats states as temporary, context-dependent snapshots rather than primitive building blocks. Particles appear as stable defects in patterns of coherence, spacetime geometry emerges from the cost of transporting identity consistently, and quantum features such as superposition and entanglement arise from unresolved or non-factorizable higher relations. A compact finite model based on the genetic code illustrates how many distinct symbolic presentations can collapse into far fewer stable meanings while preserving rich local adjacency, redundancy, and topology. The result is a research program for an equivalence-first physics whose goal is to recover established theories as limiting cases while generating new, potentially testable questions about coherence, dimensionality, observation, and the deep architecture of physical law.

Keywords: equivalence-first physics, univalent relational dynamics, category theory, homotopy type theory, relational ontology, emergent spacetime, coherence transport, topological defects, quantum foundations, genetic code model, identity as path, mathematical physics, univalence principle, moduli structures, higher categories.

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https://orcid.org/0009-0004-4206-4253

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1. The Limits of State-Based Physics

Most of modern physics begins by specifying a collection of possible states for a system. A classical particle is described by its position and momentum at a given moment. An electromagnetic field is described by values of the electric and magnetic vectors at every point in space and time. A quantum system is described by a vector in a mathematical space of possibilities, or by a more general object that encodes probabilities. Once the space of states is defined, the theory supplies rules for how one state changes into another: trajectories in classical mechanics, the Schrödinger equation or its relativistic versions in quantum theory, and partial differential equations derived from an action principle in field theory. Observables are quantities that can be measured, and they act on these states to produce numbers we can compare with experiment. This approach has produced extraordinary predictive success across scales from subatomic particles to the large-scale structure of the universe.

The framework carries an implicit picture of what reality is like. States appear as the fundamental units. A physical system possesses a state, and that state carries the information about what is real at a given time or place. Change is then understood as a sequence or continuous evolution of such states. Measurement is a procedure that reveals or alters the state. Symmetry and equivalence enter the story later, as relations imposed on an already existing collection of states. Two different mathematical descriptions are declared physically equivalent when they yield the same observable predictions or when one can be obtained from the other by an allowed transformation. The state itself remains the primary bearer of physical content.

1.1 The standard picture of states, observables, and trajectories

Consider how this picture operates in everyday physical reasoning. In classical mechanics a point particle moves along a definite path through a space whose coordinates are position and momentum. At each instant the system occupies one point in that space, and the laws of motion determine the next point. In field theory the state is a function that assigns numbers or vectors to every location in spacetime; the dynamics tell how that function evolves. In quantum mechanics the state may be a vector whose components encode amplitudes for different possible outcomes; the evolution is unitary, preserving the total probability. In statistical mechanics a macroscopic state such as temperature or pressure corresponds to an enormous number of underlying microscopic configurations. In every case the theory first defines what counts as a possible state and then describes lawful change among those states.

Observables fit naturally into the same structure. Position, momentum, energy, charge, and field strength are treated as quantities that take definite or probabilistic values once the state is specified. The mathematical representation of an observable is an operator or a function that

acts on the state space and returns a number or a distribution of numbers. This organization makes calculation straightforward and connects directly to laboratory practice: prepare a system in a known state, let it evolve according to the dynamical law, and measure an observable to test the prediction.

1.2 Equivalence introduced later through gauges, coordinates, and symmetries

Equivalence appears in this framework as a subsequent step. After the space of mathematical descriptions has been introduced, a rule is added that identifies certain descriptions as physically indistinguishable. In electromagnetism the vector potential is not unique; any two potentials that differ by the gradient of a scalar function describe the same electric and magnetic fields. In general relativity the metric tensor that encodes geometry can be rewritten in different coordinate systems without changing the intrinsic curvature or the paths of freely falling objects. In quantum mechanics a global phase factor multiplying the state vector has no observable consequence. In particle physics two electrons are treated as indistinguishable, so swapping their labels does not create a new physical situation. In statistical mechanics vastly different arrangements of molecules can correspond to the same temperature and pressure.

The standard procedure can be summarized in three stages. First one defines a large space P of mathematical presentations. Next one imposes an equivalence relation that declares certain presentations to represent the same physical situation. Finally one forms the quotient space M of physical states, in which each point stands for an entire equivalence class. Distinct presentations p1 and p2 in P are regarded as physically identical precisely when they are related by the chosen equivalence. This construction removes apparent redundancy while preserving the predictive content of the theory.

The procedure is powerful and has been refined over decades. Gauge theories systematize the handling of surplus mathematical structure. General relativity makes coordinate independence a central principle. Quantum mechanics distinguishes rays from vectors. Statistical mechanics explains how macroscopic regularity emerges from microscopic multiplicity. Yet in every case equivalence is introduced after the presentations have already been defined. The presentations come first; the identifications that remove redundancy come second.

1.3 Conceptual tensions created by treating equivalence as secondary

Treating equivalence as secondary creates persistent conceptual friction. The vector potential in electromagnetism contains more information than the observable fields, yet only the fields are supposed to be real. Different coordinate charts in general relativity describe the same geometry, yet the coordinates themselves have no invariant meaning. A quantum state vector and the same vector multiplied by a phase are supposed to represent one and the same physical situation, yet the mathematics treats them as distinct. Macroscopic thermodynamic

quantities correspond to enormous numbers of microstates, yet the theory must still explain why only certain coarse-grained descriptions are relevant to observation.

These tensions are not merely technical inconveniences. They suggest that the initial choice of what counts as a state already contains more structure than is physically necessary. The surplus shows up as gauge freedom, coordinate arbitrariness, global phases, and statistical degeneracy. Physicists have developed sophisticated tools to manage the surplus, but the tools are applied after the fact. The underlying ontology still begins with states as primary and adds equivalence relations to clean up the description.

The friction becomes sharper when one asks what it means for two presentations to be physically the same. The answer is usually given by listing the transformations that are allowed: gauge transformations, coordinate changes, unitary operators up to phase, permutations of identical particles. These transformations are not arbitrary; they preserve certain structures that the theory regards as physically significant. The question then arises whether those preserved structures, rather than the states themselves, should be taken as the starting point. If the identity of a physical situation is defined by the transformations under which it remains unchanged, perhaps the transformations deserve to be placed earlier in the explanatory order.

Further tension appears when one considers how identity persists through change. A particle can accelerate, interact, or be viewed from a moving frame and still be regarded as the same particle. A field configuration can be rewritten in a different gauge and still describe the same physical situation. A quantum system can undergo unitary evolution and still represent the same abstract state up to an overall phase. In each case persistence is secured by a family of transformations that connect the different presentations. The transformations do not merely relate already existing states; they constitute the criterion by which the states are counted as the same entity at different times or in different contexts.

These observations do not invalidate the successes of state-based physics. They indicate that the conventional starting point leaves an explanatory gap. The gap concerns the origin and status of the very equivalences that make physical interpretation possible. Closing that gap requires reversing the order of explanation: begin with the relations and transformations that identify presentations with one another, and recover states as local, context-dependent appearances within that relational structure. The following sections develop this reversal using the mathematical resources of category theory and homotopy type theory, and they explore its consequences for geometry, matter, quantum phenomena, and time.

2. The Ontological Reversal

The conventional approach begins with states and later adds rules for when two states count as physically the same. The reversal proposed here places equivalence at the foundation. States are not the primary entities from which everything else is built. They are local appearances of a deeper relational structure whose identity is carried by the transformations that connect one appearance to another. This shift does not deny that measurements yield definite results or that particles and fields behave in regular ways. It changes what we take those results and behaviors to be about. Instead of asking what intrinsic substance a thing possesses, the framework asks what patterns of coherent transformation allow one description to be substituted for another while preserving everything that matters physically.

2.1 States reinterpreted as local presentations

A presentation is a description of a physical situation relative to a chosen context. The context can be a coordinate system, a gauge choice, a basis for a vector space, a level of coarse-graining, or an experimental setup. Different presentations can look quite different yet still refer to the same underlying physical reality when the right transformations connect them. A gravitational field expressed in spherical coordinates is a presentation; the same field expressed in Cartesian coordinates is another presentation. A quantum state written in one basis is a presentation; the same abstract state written in another basis is a different presentation. A field configuration before a gauge transformation and the configuration after it are two presentations of one physical situation.

No single presentation captures the full physical content on its own. The meaning of any one description depends on the family of other descriptions that can be reached from it by admissible transformations. An isolated coordinate vector or an isolated field value therefore lacks complete physical significance until the transformations that relate it to other descriptions are specified. This dependence is already familiar in practice. Physicists routinely change coordinates or gauges precisely because they know the choice is arbitrary and that the physics should remain unchanged. The reversal simply takes this practical fact and makes it foundational rather than corrective.

2.2 Physical identity constituted by admissible equivalences

Physical identity is not something a state possesses before any relations are considered. It is constituted by the equivalences that link one presentation to others. Two presentations represent the same physical entity to the extent that an admissible equivalence connects them. An admissible equivalence is a transformation that preserves the structures the theory treats as physically significant: observable predictions, causal relations, conserved quantities, topological features, or whatever else the particular context requires. Not every mathematical

correspondence counts. A random reshuffling of numbers will not do. The transformation must carry the relevant physical information intact from one presentation to the other.

This view makes identity relational rather than absolute. A presentation by itself does not declare what it is. Its identity emerges from the web of transformations that allow it to be recognized across changes of description, environment, or time. The web can be rich. There may be many distinct ways to identify two presentations, and those different ways can themselves be related by higher transformations. Some identifications may be continuously deformable into one another; others may belong to distinct topological classes. The space of possible identifications therefore carries geometric and topological information that is physically meaningful. Physical sameness is not a simple yes-or-no label. It is a structured collection of coherent connections.

2.3 Persistence through coherent transport rather than underlying substance

Persistence through time or through change is likewise reinterpreted. A particle that moves, accelerates, or collides is still regarded as the same particle because there exists a coherent way to transport its identity from one moment or one context to the next. A field that is rewritten in a new gauge remains the same field because the gauge transformation supplies an equivalence that carries all observable content along with it. A quantum system that evolves unitarily preserves its relational information because the evolution map is invertible and structure-preserving. In each case what endures is not an unchanging inner core but a pattern of equivalence that can be followed consistently.

The transport must be coherent. If a transformation takes presentation A to presentation B at one step and then B to C at the next step, the direct transport from A to C obtained by composing the two steps should agree with any other path that connects A to C. When this consistency holds, identity can be tracked reliably. When it fails, new physical phenomena appear: a particle may decay because no allowed transport preserves its original identity type; a phase transition may reorganize the equivalence structure itself; a measurement may produce a stable classical record by rendering higher alternative paths inaccessible. Topological defects persist precisely because no local transformation can remove them without violating the coherence conditions.

This perspective replaces the classical question of substance with a question of criteria. An entity exists physically to the degree that it supports a sufficiently stable and coherent pattern of identity-preserving transformations. The pattern can be simple or intricate, local or extended, fragile or robust. What matters is that the transformations compose in a consistent way and that they preserve the features the theory regards as physically relevant. States remain useful as local records, boundary conditions, and computational inputs, but they are no longer treated as

the fundamental bearers of reality. The fundamental structure is the network of equivalences that allows different local presentations to count as the same persisting entity under admissible change.

The reversal therefore sets a clear task. If physical identity and persistence are carried by relations rather than by isolated states, then the appropriate mathematical language must be one that begins with objects and the transformations connecting them. The next sections introduce category theory as that language and show how it can be enriched with higher relations to capture the full structure of physical equivalence.

3. Category Theory as a Language of Processes

The ontological reversal treats physical identity as arising from relations rather than from isolated states. To develop this idea rigorously, a mathematical language is needed that begins with connections instead of with things in themselves. Category theory supplies exactly that language. It organizes mathematical structures around objects and the transformations that link them, making processes rather than static entities the primary focus. When applied to physics, this shift aligns naturally with the view that equivalence and transport are fundamental.

3.1 Objects understood through incoming and outgoing relations

In category theory an object is not defined by listing its internal parts or by assigning it a set of intrinsic properties. It is defined by the morphisms that enter and leave it. A morphism is simply an arrow from one object to another that represents a transformation, a process, or a relation. The object itself functions as a hub whose identity is expressed by what can be done to it and what it can become under allowed operations.

This relational definition fits physical thinking more closely than the usual state-space picture. A local field configuration, an experimental preparation, a boundary condition, or a coordinate chart can be treated as an object. What matters about it is not an isolated list of numbers but the transformations that relate it to other configurations: time evolution that carries it forward, a gauge transformation that rewrites it without changing observables, a measurement that extracts information from it, or a coordinate change that re-expresses it in a different frame. The object is the point at which these processes meet.

Because identity is carried by the morphisms, two objects that participate in exactly the same pattern of incoming and outgoing relations can be regarded as equivalent even if their internal descriptions look different. The emphasis moves from “what is this thing made of?” to “what consistent transformations connect it to everything else?” This question is already central to the

equivalence-first approach. Category theory simply gives it a precise and flexible mathematical home.

3.2 Morphisms, composition, and identity arrows in physical terms

A category consists of objects together with morphisms between them. The key operation is composition: if there is a morphism from object A to object B and another from B to C, there is a composite morphism from A to C. Composition is required to be associative, so that the order of grouping chained processes does not matter. Every object also possesses an identity morphism that represents doing nothing: it maps the object to itself and serves as a neutral element for composition.

In physical language these structures acquire direct meaning. A morphism can represent time evolution, a symmetry operation, an interaction, a change of description, or the transport of identity from one context to another. Composition corresponds to performing one process after another. When a particle is accelerated by one force and then by another, the overall effect is the composite transformation. When a field is first rewritten in a new gauge and then evolved in time, the combined operation is again a single morphism. Associativity ensures that the physics does not depend on arbitrary groupings of these steps.

The identity morphism has a clear physical counterpart as well. It represents the trivial transformation that leaves a presentation unchanged. In any consistent theory there must be a way to say that nothing has happened, and that way must compose correctly with every other process. The presence of identity morphisms therefore encodes the minimal requirement that a physical description can at least refer to itself.

These rules are deliberately minimal. They do not presuppose a background space, a metric, or a notion of distance. They only require that processes can be chained and that each object can be left alone. From this sparse starting point, rich physical structure can emerge once additional conditions are imposed on which morphisms are admissible and how they compose.

3.3 Why process-centered thinking points beyond isolated entities

Ordinary state-based physics can be recovered inside category theory as a very special case: a category whose only morphisms are the identity morphisms on each object. In that category every state is completely isolated; nothing connects one state to another except the trivial act of remaining the same. Real physical theories are never this sparse. They contain time evolution, interactions, symmetries, measurements, and changes of description. Each of these is a genuine morphism that carries information from one presentation to another.

Placing processes first therefore does more than provide convenient notation. It aligns the mathematics with the physical intuition that change and relation are primary. A particle is not

fundamentally a point sitting in a state space; it is an entity that can be prepared, accelerated, scattered, detected, and re-described while remaining recognizably itself. A field is not fundamentally a function on spacetime; it is a structure that can be transformed by gauge operations, evolved according to dynamical laws, and observed through local interactions. The morphisms encode exactly these possibilities.

Because morphisms can be composed, the framework naturally accommodates chains of processes that build complex behavior from simpler steps. Because every object carries an identity morphism, the framework also accommodates the possibility of doing nothing. Most importantly, because identity is expressed through the pattern of morphisms rather than through an internal essence, the same formal language can later accommodate the richer notion of equivalence developed in the preceding section. Two presentations count as physically the same when there exists a morphism between them that preserves the relevant structures and that can be coherently composed with other morphisms.

This process-centered view therefore supplies the minimal architecture needed for an equivalence-first physics. It treats objects as provisional and relations as fundamental. The next step is to recognize that physics often requires relations among the relations themselves. Gauge transformations can be deformed into one another, alternative histories can be continuously compared, and higher coherence conditions can constrain which patterns of transport are physically allowed. These considerations lead beyond ordinary categories to higher categorical structures, which are introduced in the following section.

4. Higher Relations, Paths, and Structured Identity

Ordinary category theory already treats processes as fundamental, but many physical situations require more. Transformations themselves can be compared, deformed, or related in ways that carry physical consequences. Two gauge transformations may achieve the same effect yet differ by a continuous deformation. Two paths through spacetime may be continuously stretchable into each other or may wind around an obstacle in topologically distinct ways. Two quantum histories may accumulate different phases even when they connect the same initial and final presentations. These comparisons are not merely mathematical bookkeeping; they encode measurable effects such as phases, holonomies, and obstructions. Capturing them requires a richer language in which relations exist between relations.

4.1 When transformations between transformations carry physical content

In basic category theory a morphism goes from one object to another. When physics needs to relate two such morphisms, a new layer appears. A transformation between two transformations is called a 2-morphism. It represents the idea that one process can be

continuously or discretely changed into another while preserving the structures that matter. In gauge theory, for example, two gauge functions that produce the same field strength can often be deformed into each other through a family of intermediate gauge functions. The deformation itself is physically relevant because it can contribute to topological invariants or to the spectrum of allowed excitations.

Similar layering occurs whenever alternative routes or histories exist between the same endpoints. In general relativity, two paths connecting the same pair of events may be deformable into each other or may belong to distinct homotopy classes distinguished by winding around a massive body. In quantum mechanics, different sequences of measurements or different paths in a path integral can interfere constructively or destructively precisely because they are related by higher-level comparisons. In each case the physics is sensitive not only to whether two presentations can be connected, but to how they are connected and whether those connections can themselves be varied continuously.

Once 2-morphisms are admitted, the pattern continues. Two 2-morphisms can be related by a 3-morphism, and so on. The hierarchy does not stop at any fixed level. This open-ended structure is exactly what is needed to describe the full richness of physical equivalence. Some identifications between presentations are unique up to continuous deformation; others fall into discrete families separated by topological barriers. Some loops of transformations can be shrunk to a point; others cannot. These distinctions are not decorative. They appear in measurable quantities such as Berry phases, Aharonov-Bohm effects, and the classification of defects and phases of matter.

4.2 Infinity-groupoids and reversible structure at every level

A groupoid is a category in which every morphism is invertible. For every arrow from A to B there exists an arrow back from B to A that undoes the first. This reversible structure fits the part of physics concerned with equivalence and sameness. Gauge transformations, coordinate changes, and unitary evolutions are typically invertible; one can go back as well as forward while preserving the relevant physical content.

An infinity-groupoid extends the idea to all higher levels. Objects are connected by invertible 1-morphisms (paths). Those paths are connected by invertible 2-morphisms (continuous deformations between paths). The deformations are connected by invertible 3-morphisms, and the process continues without an upper bound. The resulting structure models a space in which identity is not a single rigid link but a rich, layered web of reversible connections.

In physical terms this means that sameness can possess internal topology. Returning to the same presentation after a closed sequence of transformations does not necessarily mean that nothing happened. The loop may carry a phase, a rotation, or a topological charge. Different

loops may be deformable into one another or may be separated by obstructions that cannot be removed without breaking the allowed transformations. These features correspond directly to conserved quantities, selection rules, and the classification of particles and defects. The infinity-groupoid therefore supplies a natural mathematical home for the reversible aspect of physical identity while leaving room for irreversible processes to be added later through a broader categorical structure.

4.3 Identity as paths rather than simple yes-or-no declarations

The homotopy-theoretic view of identity treats the statement that two presentations are the same not as a simple true-or-false label but as a structured object in its own right. An identification is a path connecting one presentation to the other. Paths can be composed end-to-end when the endpoint of one matches the starting point of the next. Every presentation possesses a constant path that stays at home and represents trivial identity. Paths can be reversed, corresponding to the inverse transformation that undoes an equivalence.

Higher identity structure appears when two paths between the same pair of presentations can themselves be compared. A higher path represents a continuous deformation that turns one identification into another. The existence of such deformations, or their absence, carries physical information. In some situations every identification can be deformed into every other; the equivalence is essentially unique up to continuous change. In other situations distinct families of identifications exist that cannot be continuously transformed into one another; these families correspond to different topological sectors or to different ways of realizing the same physical situation.

This structured notion of identity replaces the binary question “Are these two presentations the same?” with a richer set of questions: How many distinct ways exist to identify them? Can those ways be continuously deformed into one another? What happens when identifications are transported around closed loops? The answers to these questions determine observable consequences. They also prepare the ground for the principle of univalence, which states that suitably structured equivalence can itself serve as physical identity rather than merely indicating similarity. That principle, and its physical consequences, are developed in the next section.

5. Univalence as a Physical Principle

The preceding sections have established that physical identity is carried by structured relations rather than by isolated states, and that these relations can themselves be compared and deformed at higher levels. The principle of univalence supplies the final conceptual step. It asserts that, under appropriate conditions, structural equivalence can itself constitute physical identity. Two presentations are not merely similar or related; when a sufficiently coherent

equivalence connects them, they count as the same physical reality. This principle turns the relational view into a precise foundation rather than a philosophical preference.

5.1 The correspondence between structural equivalence and physical sameness

In ordinary language and in much of mathematics, equivalence and identity are kept distinct. Two objects can be equivalent in some respect without being regarded as literally the same thing. Univalence proposes that, once the right notion of structure is fixed, a well-behaved equivalence can be promoted to an identity. In the mathematical setting this appears as a correspondence between the type of identifications between two objects and the type of structure-preserving equivalences between them. When the correspondence holds, saying that two objects are identical is interchangeable with exhibiting a coherent equivalence between them.

Translated into physics, the principle reads that two local presentations represent one and the same physical entity precisely when an admissible equivalence connects them. The equivalence must be reversible and must preserve the features the theory treats as physically meaningful. Gauge-equivalent field configurations are not merely similar descriptions of one situation; under the univalent reading they are the same situation. Coordinate-related metrics in general relativity are not merely numerically close; they are alternative presentations of one geometry. Different bases for the same abstract quantum state are not merely convenient rewritings; they are different views of one relational structure. The principle does not claim that every mathematical resemblance is physical identity. It claims that when an equivalence preserves the relevant physical content and can be coherently transported and composed, that equivalence can be used as the definition of sameness.

5.2 Admissible equivalences and what they are required to preserve

Not every mathematical correspondence qualifies as a physical equivalence. An admissible equivalence must preserve the structures that the particular physical context regards as invariant. In one setting the preserved structures may be observable probabilities and expectation values. In another they may be causal relations or the light-cone structure. In still another they may be topological invariants or conserved charges. The theory must specify, at least locally, which features are to be held fixed under the allowed transformations.

The requirement of admissibility prevents the principle from collapsing into the claim that “everything is the same as everything else.” A random reassignment of field values or a discontinuous jump in coordinates will not preserve the necessary structures and therefore will not count as an admissible equivalence. Only those transformations that carry the physically relevant information intact are promoted to identities. This selectivity is what allows the framework to recover the successful distinctions of existing physics while reinterpreting their

status. Gauge transformations in electromagnetism preserve the field strengths; coordinate transformations in general relativity preserve the curvature and the geodesic structure; unitary operators in quantum mechanics preserve probabilities and expectation values. Each of these classes of transformations is admissible within its domain precisely because it respects the invariants the theory has already identified as physically significant.

5.3 Equivalence spaces instead of binary equivalence predicates

Once identity is tied to equivalence, it becomes natural to ask how many distinct equivalences exist between two given presentations and how those equivalences are themselves related. The answer is not a single yes-or-no declaration. It is a space whose points are the admissible equivalences connecting the two presentations. This space can possess its own geometry and topology. It may contain several disconnected components, each corresponding to a qualitatively different way of identifying the presentations. It may contain closed loops, indicating that some equivalences possess internal symmetries. It may contain higher-dimensional families of deformations, indicating that identifications can be varied continuously while remaining admissible.

These features are directly physical. Distinct components of the equivalence space can label different topological sectors or different superselection rules. Non-contractible loops can generate phases or conserved quantities. The volume or measure of the space can influence statistical weights or transition amplitudes. In short, the internal organization of the space of equivalences is not auxiliary information; it is part of the physical content that the univalent principle brings into view.

Treating equivalence as structured rather than binary also clarifies why merely rewriting known physics in categorical language is insufficient. The goal is not to relabel existing concepts but to derive new consequences from the richer geometry of equivalence spaces. Once identity is allowed to have internal structure, new questions become natural: How does the cost or complexity of an equivalence affect dynamics? What obstructions arise when equivalences are transported around closed paths? How do measurements truncate or project the higher structure of equivalence spaces? These questions are taken up by the axioms and dynamical principles developed in the following sections.

6. The Axioms of Univalent Relational Dynamics

The univalent principle states that suitably structured equivalence can serve as physical identity. To turn this principle into a working framework, a small set of axioms is needed. These axioms do not dictate the detailed laws of any particular theory. They specify the minimal conditions under which a relational, equivalence-first description of physics can be consistent and useful.

Each axiom has a direct physical reading and a clear mathematical counterpart in the language of categories and higher structures.

6.1 Presentation, univalent identity, and higher-coherence axioms

The first axiom concerns the status of what we actually observe. Every concrete description of a physical situation is a presentation relative to some context: a choice of coordinates, a gauge, a basis, an experimental arrangement, or a level of description. No single presentation exhausts the underlying physical identity. A field value written in one gauge is a presentation; the same physical situation written in another gauge is a different presentation. The axiom simply records that all observational access is contextual and therefore partial.

The second axiom links presentations to identity. Two presentations represent the same physical entity precisely to the degree that an admissible equivalence connects them. This is the direct physical reading of univalence. The equivalence must be reversible and must preserve the structures regarded as physically significant in the given context. When such an equivalence exists and can be coherently transported, the two presentations are counted as one and the same reality rather than as merely similar descriptions.

The third axiom concerns relations among equivalences. Equivalences between equivalences, and higher relations among those, possess physical content whenever they affect composition, transport, obstruction, or observation. A continuous deformation between two gauge transformations, for example, is not merely a mathematical curiosity; it can determine whether certain topological charges are conserved or whether certain interference effects appear. The axiom therefore requires that the higher layers of structure be retained rather than discarded once a single equivalence has been found.

6.2 Observable descent, compositionality, and local-to-global principles

Observables must respect equivalence. If two presentations are connected by an admissible equivalence, then any observable applied to them must return results that are themselves equivalent in the appropriate sense. This descent condition prevents observables from depending on arbitrary choices of presentation. It is the relational counterpart of the familiar requirement that physical predictions be gauge-invariant or coordinate-independent. When the condition holds, observables become well-defined functions on the space of physical meanings rather than on the larger space of raw presentations.

Physical processes must compose. A transformation that carries one presentation into another, followed by a transformation that carries the second into a third, defines a composite transformation from the first to the third. The composition must be coherent: different ways of grouping a chain of processes must yield equivalent results. This axiom encodes the minimal

consistency requirement that allows identity to be tracked reliably across multiple steps. Without it, there would be no stable notion of persistence through sequences of changes.

Globally meaningful physical structures arise by coherently gluing compatible local presentations and local equivalences. The axiom does not assume that a single global description is always available or privileged. It states that when local pieces fit together consistently along their overlaps, a global structure can be assembled. When they fail to fit, the obstruction itself becomes a physical phenomenon. Defects, topological charges, and certain quantization conditions appear precisely as such obstructions to global gluing. The axiom therefore treats both successful assembly and the failure of assembly as physically significant.

6.3 Dynamics and finite observation as truncation

Dynamics governs the formation, transport, deformation, stabilization, and failure of equivalence structures. Rather than describing how one state changes into another, the dynamical laws describe how equivalences are created, moved, bent, preserved, or broken. Curvature, for example, appears as the obstruction encountered when identity is transported around a closed loop and fails to return unchanged. Phase factors and holonomies arise from the same transport process. The axiom therefore places the evolution of relational structure at the center of dynamics.

Actual observations access only truncated portions of the higher relational structure. A measurement yields a definite classical outcome by rendering higher distinctions among alternative presentations inaccessible. The full space of equivalences and higher paths is not directly available to any single observation. Classical facts emerge when the higher layers are effectively projected or coarse-grained away. This truncation is not an imperfection of the observer; it is a structural feature of finite interaction with an infinitely structured relational reality. The axiom therefore explains why classical descriptions appear at all while preserving the richer higher structure for the underlying dynamics.

Taken together, the axioms define a consistent relational framework without presupposing a background spacetime, a fixed set of fundamental states, or a privileged level of description. They allow states to reappear as useful local records while locating physical identity in the equivalences that connect those records. The next sections show how these axioms generate concrete mathematical structures, such as moduli spaces of physical meanings and dynamical principles based on the cost of coherent transport.

7. Presentation Spaces, Moduli, and the Geometry of Meaning

The axioms require that physical identity be carried by equivalences rather than by isolated states. To make this requirement operational, the space of all possible descriptions must be organized so that the equivalences are visible and usable. The mathematical structures that achieve this organization are presentation spaces and their moduli. These structures replace the simple notion of a quotient set with a richer geometry that retains the internal relations among presentations.

7.1 Redundant descriptions and the move from sets to groupoids

Any physical theory generates more mathematical descriptions than are needed to label distinct physical situations. The same electromagnetic field can be written with many different vector potentials. The same spacetime geometry can be expressed in many coordinate systems. The same abstract quantum state can be written in many different bases. These descriptions are not errors; they are redundant presentations of the same underlying reality. The collection of all such presentations forms a space P.

If one simply declares that two presentations are equivalent and then discards the distinction between them, a great deal of useful information disappears. One no longer knows how many distinct transformations connect a given pair of presentations, whether those transformations can be continuously deformed into one another, or what symmetries each presentation possesses. The ordinary set-theoretic quotient forgets exactly the relational data that the equivalence-first approach treats as physically significant.

Category theory replaces the simple quotient with a groupoid. In a groupoid the objects are the presentations, and the morphisms are the admissible equivalences that connect them. Each morphism records an explicit transformation rather than merely asserting that two presentations belong to the same class. Composition of morphisms records how transformations chain together. The groupoid therefore keeps the full relational structure visible while still allowing one to speak of presentations that represent the same physical meaning.

7.2 Homotopy quotients that retain stabilizers, loops, and higher relations

The passage from the space of presentations to the space of physical meanings is performed by a homotopy quotient rather than by an ordinary set quotient. Symbolically, the physical moduli space M is obtained as M = P // E, where E stands for the admissible equivalence structure. The double slash indicates that the construction retains more than the mere grouping of presentations into classes.

In the homotopy quotient, each physical meaning m is represented not by a single point but by the entire collection of presentations that realize it, together with all the equivalences

connecting those presentations. The fiber over m therefore contains the transformations that relate different descriptions of the same physical situation. These transformations include loops that begin and end at the same presentation; such loops encode internal symmetries or phases. They also include higher relations among the transformations, which record how one way of identifying two presentations can be continuously deformed into another.

Because the construction keeps this internal structure, physical distinctions that would be invisible in an ordinary quotient remain visible. Two presentations that belong to the same equivalence class may still be connected by inequivalent transformations that cannot be deformed into each other. Those inequivalent transformations can label different topological sectors or different ways of realizing the same coarse physical situation. The homotopy quotient therefore supplies a geometry of meanings in which both the identifications and the distinctions among identifications are retained.

7.3 Automorphism groups and homotopy invariants as carriers of physical labels

Each presentation x possesses a collection of self-equivalences, that is, admissible transformations from x back to itself. These self-equivalences form the automorphism group Aut(x). In physical terms the automorphism group encodes the internal symmetry or degeneracy of the presentation. A highly symmetric configuration admits many distinct automorphisms; a generic configuration admits fewer. The size and structure of Aut(x) can therefore serve as a label that distinguishes physically different situations even when they belong to the same coarse equivalence class.

Higher homotopy information supplies additional labels. The connected components of the moduli space correspond to sectors that cannot be continuously deformed into one another. Loops within a component correspond to phases or holonomies that are accumulated when identity is transported around closed paths. Higher homotopy groups capture relations among those loops and obstructions to further deformations. These invariants are not auxiliary mathematical decorations; they correspond to conserved charges, selection rules, and the classification of defects and phases.

The geometry of the moduli space therefore carries physical content directly. Distance or proximity in this space can be defined by the existence and cost of coherent equivalences between presentations. Curvature or topological features of the space can reflect obstructions to transporting identity consistently. The entire construction remains background-independent: no pre-existing spacetime or state space is assumed. The geometry emerges from the pattern of admissible equivalences once the presentation space and the equivalence structure have been specified.

This organization of presentations and meanings sets the stage for dynamics. Once physical meanings are located in a moduli space whose internal geometry records the relations among presentations, the evolution of a system can be described as the transport of identity along paths in that space. The cost, coherence, and obstructions associated with such transport then become the raw material for dynamical laws. Those laws are developed in the following section.

8. Dynamics as Transport and the Cost of Coherence

Once physical meanings are organized in a moduli space whose geometry records the relations among presentations, dynamics can be reinterpreted. Instead of describing how one state moves to another through a pre-existing space, dynamics describes how identity is carried from one presentation to another by coherent transformations. The laws of motion become rules for the formation, transport, deformation, and obstruction of these equivalences. Geometry and curvature emerge as consequences of consistency requirements on the transport rather than as background structures imposed in advance.

8.1 Replacing trajectories with composable families of transformations

In the conventional picture a system follows a trajectory x(t) through a state space. The parameter t is usually interpreted as time, and the path is governed by differential equations derived from an action or from a Hamiltonian. The equivalence-first view replaces the primitive trajectory with a family of transformations that carry one local presentation into another. These transformations are morphisms in the underlying category or groupoid. They compose when one process is followed by another, and the composition must satisfy coherence conditions so that different sequences of steps yield consistent results.

A presentation at one moment or in one context is connected to a presentation at a later moment or in a different context by a transport map. The transport map does not merely relate two states; it carries the identity of the physical entity along with it. When the transport is invertible and preserves the relevant structures, the entity at the later presentation is counted as the same entity that existed earlier. The entire history of the system is therefore encoded in a composable chain of such transport maps rather than in a curve drawn through a fixed state space.

This replacement has immediate consequences. Because transport maps can be composed, the dynamics automatically handles sequences of processes without requiring an external time parameter at every step. Because the maps must be coherent, consistency conditions appear naturally as soon as one considers alternative paths between the same initial and final presentations. These consistency conditions are the source of curvature and of the geometric structures that will later be identified with spacetime.

8.2 Coherence around loops, holonomy, and the meaning of curvature

Consider a closed sequence of transformations that begins and ends at the same presentation. After transporting identity all the way around the loop, one can compare the final transported structure with the original identity map. If the comparison yields the identity transformation exactly, the loop is said to close trivially. If the comparison yields a non-trivial result, a phase, a rotation, or a more general transformation has been accumulated. This non-trivial return is called holonomy.

Holonomy is not an accident of calculation; it records an obstruction to consistent identity transport. In physical terms the obstruction appears as curvature. When identity is carried around a small closed path and fails to return unchanged, the failure is attributed to curvature at the location enclosed by the path. Larger loops can enclose regions of varying curvature or can wind around topological defects that cannot be removed by any allowed local transformation. The same mechanism generates Berry phases in quantum systems, Aharonov-Bohm phases around solenoids, and parallel-transport effects in gravitational fields.

The key point is that curvature is not introduced as an independent geometric field. It arises as a derived consequence of demanding that identity transport be coherent around every possible loop. Where the demand can be satisfied everywhere, the geometry is flat. Where it cannot, curvature or defects appear. This derivation reverses the usual explanatory order: geometry is not the arena in which dynamics occurs; it is the record of how consistently identity can be transported through the relational structure.

8.3 A relational action principle and the notion of equivalence geodesics

To turn the transport picture into quantitative dynamics, a measure of cost is required. Each admissible equivalence or transport map can be assigned a cost that reflects how much structure must be preserved or how much deformation is needed to carry identity from one presentation to another. Low-cost transformations correspond to physically proximate or easily related presentations. High-cost transformations require more elaborate adjustments and are therefore regarded as more distant.

A schematic relational action can be written by summing costs over the edges of a network of presentations, adding penalties for failures of loop closure, and including local terms that measure incompatibility at individual presentations. The action is extremized when the network realizes the greatest possible coherent equivalence for the lowest total cost. Solutions to this variational problem define equivalence geodesics: paths through the space of presentations that minimize the coherence cost between given initial and final meanings.

In the continuum limit the discrete network of presentations and transport maps can be replaced by smooth fields and differential operators. The cost functional then reproduces

familiar expressions involving covariant derivatives, curvature scalars, and potential terms. The geodesic equation recovered from the variational principle becomes the equation of motion for identity transport. In this way the relational action supplies a bridge between the discrete, equivalence-centered description and the differential equations of conventional physics.

The same construction also yields conservation laws as invariants preserved by families of equivalences. Quantities that remain unchanged under all admissible transports are conserved. The relational action therefore recovers both the dynamical trajectories and the conservation principles of established theories while locating their origin in the cost and coherence of identity transport rather than in an assumed background geometry or state space.

This dynamical framework prepares the ground for the emergence of spacetime itself. Once distance, curvature, and causal structure can be derived from the cost and consistency of transporting identity, the familiar geometric arena is no longer fundamental. It becomes a derived description of relational patterns. The following section develops this emergence explicitly.

9. Spacetime and Gravity Emerging from Relational Transport

The dynamical framework treats identity as something that must be transported coherently from one presentation to another. Once a cost is assigned to each admissible transport, geometric notions such as distance, proximity, and curvature can be derived directly from the pattern of costs and consistencies. Spacetime is not assumed as a pre-existing stage on which physics plays out. It emerges as a description of how identity can be moved reliably through the relational structure.

9.1 Relational proximity and distance defined by coherence cost

Two presentations or contexts are regarded as physically near when a low-cost, coherent equivalence connects them. The cost reflects the amount of structure that must be preserved or the degree of deformation required to carry identity from one to the other. When many low-cost equivalences exist between two presentations, they lie close together in the moduli space of physical meanings. When only high-cost or obstructed equivalences exist, the presentations are regarded as distant.

A candidate notion of distance follows at once. The distance between two physical meanings x and y is defined as the infimum of the costs of all admissible equivalences connecting them. In symbols this can be written $d(x,y) = \inf \{ C(e) \mid e \text{ connects } x \text{ to } y \}$, where the infimum is taken over the space of allowed transport maps. This definition makes proximity a derived rather than a primitive concept. There is no background metric that tells us which presentations are near;

nearness is simply the existence of cheap, reliable ways to identify one presentation with another.

The same construction generates neighborhoods before it generates numerical distances. A neighborhood of a given meaning consists of all other meanings that can be reached by equivalences whose cost lies below some threshold. These neighborhoods can be used to define continuity and limits without ever presupposing a coordinate grid or a metric tensor. The topology of the moduli space therefore arises from the density and connectivity of low-cost equivalences rather than from an assumed spatial background.

9.2 Curvature as obstruction to trivial identity return

Curvature appears when identity transport around a closed loop fails to return to the original transformation. After carrying identity all the way around the loop, one compares the final transported structure with the identity map that would have been obtained by doing nothing. Any mismatch is recorded as curvature enclosed by the loop. Small loops probe local curvature; larger loops can enclose regions of varying curvature or can detect global topological features.

This derivation reverses the usual order of explanation. In conventional geometry one first posits a curved manifold and then studies parallel transport on it. Here one begins with the requirement that identity transport be coherent and discovers curvature as the inevitable consequence of local inconsistencies in that transport. The curvature scalar, the Ricci tensor, and the full Riemann curvature can be recovered in the continuum limit as measures of how much the transport maps deviate from perfect closure around infinitesimal loops.

The same mechanism accounts for gravitational effects. The equivalence principle states that local acceleration is indistinguishable from a gravitational field. In the relational framework both phenomena appear as position-dependent modifications of the cost and coherence of identity transport. An observer in a gravitational field finds that transporting identity from one location to another accumulates holonomies that cannot be removed by any local redefinition of coordinates or gauges. These holonomies are the relational signature of spacetime curvature.

9.3 Background independence and the emergence of causal and metric structure

Because distance, curvature, and neighborhoods are all derived from the pattern of admissible equivalences and their costs, no pre-existing spacetime arena is required. The geometry is background-independent by construction. One begins with a space of presentations and a structure of equivalences; the geometric notions emerge afterward as descriptions of how identity can be transported consistently. This independence is not an extra postulate but a direct consequence of placing equivalence first.

Causal structure can emerge alongside the metric. When some morphisms are directed and noninvertible while others remain locally reversible, a distinction between timelike and spacelike directions appears naturally. Irreversible processes define a partial order: one presentation can influence another only if there exists a directed chain of morphisms connecting them. Reversible equivalences, by contrast, can be traversed in either direction without changing the physical identity. The resulting causal cones and lightlike boundaries arise from the asymmetry between reversible and irreversible morphisms rather than from an assumed Lorentzian metric.

Dimensionality itself can emerge from the growth rate and connectivity pattern of the equivalence network. In regimes where low-cost equivalences are densely connected in many independent directions, an effective high-dimensional geometry appears. In regimes where connections are constrained to lower-dimensional substructures, the effective dimension drops. No fixed number of spacetime dimensions needs to be imposed at the outset.

The relational framework therefore supplies a route to emergent spacetime in which geometry, causality, and dimension are all secondary descriptions of the underlying pattern of coherent identity transport. Gravitational dynamics, in this view, is the dynamics of that transport: the tendency of the relational structure to extremize coherent equivalence while minimizing the cost required to sustain it. The following section shows how matter and particles arise as stable patterns and defects within the same emergent geometry.

10. Matter, Particles, and Charge as Coherence Phenomena

The emergent geometry developed in the previous section arises from the cost and consistency of transporting identity through a network of equivalences. Within that same relational structure, stable localized patterns can appear. These patterns behave as matter. Particles are not inserted into spacetime as separate objects; they are stable defects or coherent substructures that persist because they cannot be removed by any allowed local transformation. Mass, charge, and interactions then receive natural interpretations as aspects of how these patterns are maintained and exchanged.

10.1 Persistent relational patterns and particles as topological defects

A physical object can be defined as a pattern of equivalences that can be transported from one context to another while retaining a coherent identity type. The pattern need not be point-like or rigid. It can be extended, deformable, or even topologically nontrivial, provided the transport maps compose coherently and preserve the structures regarded as physically significant.

When such a pattern is localized and cannot be continuously deformed away by any allowed local equivalence, it behaves as a particle-like entity. In the relational picture this corresponds to a topological defect in the equivalence field. Just as a knot in a rope cannot be removed without cutting or passing the end through a loop, certain localized obstructions in the web of equivalences cannot be trivialized by any continuous family of admissible transformations. These obstructions persist through transport and therefore register as stable particles.

Different types of defects arise from different homotopy classes of the equivalence structure. Some defects carry conserved charges because any attempt to remove them would violate the coherence conditions. Others are neutral but still stable because they represent the lowest-energy configuration within their topological sector. Composite objects form when multiple defects are bound together by regions of coherent equivalence that link them without allowing separation. In every case the particle is not a primitive ingredient added to geometry; it is a stable, transportable feature of the geometry itself.

10.2 Mass as the inertia of maintaining coherence under transport

Mass appears as the cost associated with preserving and moving a coherent pattern. When a defect or localized pattern is transported along a path, a certain amount of relational structure must be maintained at each step. The minimal cost of that maintenance, in the appropriate low-energy limit, is proportional to the length of the path. In schematic form the transport cost C for a pattern E along a path gamma satisfies C(E, gamma) approximately equal to m times the path length, where m is identified with the rest mass.

This identification makes mass a measure of equivalence inertia rather than an intrinsic property of a point particle. A massive pattern resists changes in its transport because any deviation would increase the coherence cost. A massless excitation, by contrast, can propagate without incurring an intrinsic rest-frame cost; its coherence is maintained by the propagation itself. The distinction between massive and massless behavior therefore arises from whether the pattern requires ongoing relational maintenance even when it is not moving through the emergent geometry.

Rest mass can be understood as the cost of maintaining internal coherence even in the absence of translational motion. A particle at rest still supports a nontrivial pattern of self-equivalences and higher relations. The energy associated with sustaining that pattern appears as rest mass. When the particle moves, additional transport costs appear, but the underlying maintenance cost remains. This separation between rest-frame coherence and translational transport reproduces the familiar relativistic relation between mass, energy, and momentum while locating both in the relational cost structure.

10.3 Charge as response to internal automorphism structure; interactions as coherence exchange

Charge is carried by the way a physical identity responds to its own internal symmetries. Each presentation x possesses an automorphism group Aut(x) consisting of the admissible self-equivalences that map it to itself. When the pattern representing a particle transforms nontrivially under these automorphisms, the transformation properties label the particle with charge quantum numbers. Different representations of the same automorphism group correspond to different charges or to particles and antiparticles.

Interactions arise when two or more coherence patterns approach one another and their identity structures begin to factor, compose, or obstruct one another. In the relational language an interaction is a change in the global pattern of equivalences caused by the local overlap or merging of defects. The interaction may create new bound states, exchange charge, or alter the topological class of the participating patterns. Because the underlying structure is categorical, these processes are described by composition, tensor products, limits, and colimits rather than by forces acting at a distance.

The same framework accommodates both fundamental and composite matter. Fundamental defects correspond to irreducible patterns that cannot be decomposed further within the allowed equivalences. Composite objects arise when multiple defects are glued together by coherent regions that preserve the overall identity while allowing internal relative motion or excitation. Decay and creation processes appear as changes in the topological or coherence class of the defect network. In every case the dynamics remain the dynamics of equivalence transport and cost; matter is simply the stable, localized, and interacting part of that dynamics.

This relational account of matter prepares the ground for a re-examination of quantum phenomena. Superposition, entanglement, and measurement can now be understood as features of how higher relational structure is retained or truncated rather than as mysterious additions to a classical particle ontology. Those features are developed in the following section.

11. Quantum Phenomena Reinterpreted Through Relations and Truncation

Quantum mechanics has long been interpreted through the language of state vectors, Hilbert spaces, and operators acting on them. The equivalence-first framework offers a different starting point. Quantum features arise from the higher relational structure that connects presentations and from the way that structure is accessed or truncated by actual observations. Superposition, interference, entanglement, and measurement are re-described as aspects of how multiple coherent paths and higher identities are retained or projected rather than as intrinsic properties of isolated quantum states.

11.1 Amplitudes arising from summation over equivalence paths

In the conventional path-integral formulation, transition amplitudes are obtained by summing contributions from all possible trajectories connecting an initial state to a final state. Each trajectory is weighted by a phase factor determined by the classical action along that trajectory. The relational reformulation replaces trajectories through state space with paths through the space of admissible equivalences.

An amplitude connecting two physical meanings is expressed as a sum or integral over all coherent equivalences that link a presentation of the initial meaning to a presentation of the final meaning. Each equivalence carries a phase determined by the relational action associated with transporting identity along that route. Constructive or destructive interference occurs when multiple inequivalent but coherent routes contribute to the same pair of meanings. The resulting amplitude depends on the entire structured space of equivalences rather than on any single classical path.

This shift preserves the predictive content of the path integral while changing its interpretation. The integration domain is no longer a space of field configurations or particle trajectories; it is the space of admissible transformations that preserve physical identity. The stationary-phase contributions that dominate the semiclassical limit still correspond to equivalence geodesics of minimal coherence cost. Quantum corrections arise from fluctuations around those geodesics in the space of equivalences.

11.2 Superposition as unresolved higher paths; entanglement as non-factorizable identity

Superposition appears when multiple higher-level paths remain available between the same pair of presentations. Before any observation distinguishes among them, the system retains the full relational structure connecting the alternatives. The state vector of conventional quantum mechanics can be viewed as a compact encoding of this unresolved higher structure. Different components of the superposition correspond to different coherent routes that have not yet been separated by truncation.

Entanglement has a direct relational reading. When two subsystems are entangled, the joint system possesses equivalences that cannot be decomposed into independent equivalences of the separate subsystems. In the language of the framework, the space of admissible identifications for the combined system is not simply the product of the individual identification spaces. The failure of factorization means that the identity of the whole cannot be reconstructed from the identities of the parts taken separately. This non-factorizability is the relational signature of entanglement and explains why local measurements on one subsystem instantly constrain the possibilities for the other.

Contextuality follows from the same structure. Different observational contexts correspond to different choices of which equivalences are treated as admissible or which higher paths are made accessible. When no single global assignment of classical values is compatible with all local contexts simultaneously, the theory exhibits contextuality. The incompatibility is not a failure of realism but a consequence of the fact that the full higher relational structure cannot be reduced to a single classical layer without loss.

11.3 Measurement as truncation of higher structure; decoherence as loss of accessible paths

Measurement is modeled as a map that projects or truncates the higher relational structure onto a lower level. In homotopy terms this corresponds to passing from a rich space of paths and higher paths to its connected components or to a coarser quotient. The act of measurement renders most of the alternative coherent routes inaccessible, leaving only a set-like outcome that can be recorded classically. The truncation is not arbitrary; it is determined by the interaction between the system and the measuring apparatus, which effectively selects a particular family of equivalences while suppressing others.

Decoherence arises when the environment couples to the system in such a way that alternative connecting paths become practically indistinguishable or dynamically suppressed. The higher structure is not destroyed in an absolute sense, but the coherences that would allow interference between different routes are dispersed into environmental degrees of freedom that are no longer tracked. From the perspective of the observed subsystem, the space of accessible equivalences collapses toward a classical mixture. The relational account therefore explains the appearance of classical outcomes without requiring an additional collapse postulate; the collapse is the effective result of finite observational access to an infinitely structured relational reality.

The derivation of the Born rule from measures on equivalence spaces remains an open requirement of the framework. The probability of a particular outcome should ultimately follow from the geometry or measure of the space of equivalences consistent with the preparation and the measurement context. While the relational structure supplies a natural setting in which such a derivation might be attempted, the explicit construction of the measure and the justification of the rule lie beyond the present axioms and must be addressed by further development of the dynamical and statistical principles.

This relational reinterpretation of quantum phenomena completes the basic architecture. Geometry, matter, and quantum behavior have all been recovered as consequences of coherent identity transport within a network of equivalences. The final section turns to time, entropy, and irreversibility, and uses a finite toy model to illustrate how the same principles operate in a concrete combinatorial setting.

12. Time, Entropy, Irreversibility, and a Finite Motivating Model

The relational framework has so far emphasized reversible equivalences that preserve identity. Many physical processes, however, are irreversible: particles decay, measurements yield definite records, and coarse-graining erases fine distinctions. Time and entropy arise from the directed, noninvertible aspects of composition and from the growth of multiplicity in the spaces of equivalent presentations. A simple finite model drawn from the genetic code illustrates how these ideas operate in a concrete combinatorial setting and supplies a testing ground for the broader program.

12.1 Directed composition and the emergence of temporal order

Reversible morphisms represent ways in which one presentation can be transformed into another while preserving physical identity. They can be traversed in either direction without loss of coherence. Irreversible morphisms, by contrast, represent genuine production, decay, measurement, or coarse-graining. Once such a process has occurred, there is no admissible inverse that restores the original higher relational structure exactly.

Temporal order emerges from the compositional sequence of these directed processes. When a noninvertible transformation carries a presentation x into a presentation y, and another carries y into z, the composite carries x into z in a manner that cannot be undone. The resulting partial order on presentations supplies a notion of before and after that does not rely on a pre-existing time coordinate. Causality is likewise relational: one event can influence another only if there exists a directed chain of morphisms connecting them. Reversible equivalences can still connect presentations within a given “time slice,” but they do not reverse the directed flow of irreversible processes.

This account makes the arrow of time a consequence of the asymmetry between reversible and irreversible morphisms rather than an independent postulate. The second law and the increase of entropy then appear as statistical tendencies within the space of directed compositions.

12.2 Entropy as multiplicity of equivalent presentations for a given meaning

Entropy measures the number of distinct presentations that realize one coarse physical meaning. In the relational setting this is expressed by the volume of the fiber over a given point m in the moduli space: the larger the space of presentations that map to the same meaning, the higher the entropy. A schematic formula reads S_eq(m) approximately equal to k_B times the logarithm of the volume of the fiber over m. When symmetries are present, a refined counting that incorporates automorphism groups and higher homotopy data replaces the ordinary volume; highly symmetric presentations are weighted according to their stabilizer structure.

Thermodynamic evolution corresponds to movement toward macroscopic meanings that possess larger spaces of equivalent microscopic presentations. Irreversible processes increase the total multiplicity because they map many fine-grained presentations onto fewer coarse-grained ones while discarding the distinctions that would allow reversal. Information loss is therefore not an extra assumption but the direct result of truncation or coarse-graining in the relational structure.

Memory and records appear as stable asymmetries in the equivalence network. A record is a configuration that constrains which past transformations remain reconstructible from the present. The existence of such stable asymmetries allows the arrow of time to be operationally meaningful even though the underlying reversible equivalences are symmetric.

12.3 The genetic code as a compact toy universe of presentations and quotient meanings

The genetic code provides a finite, non-physical illustration of the same principles. There are 64 codons formed by triplets drawn from four nucleotide symbols. These codons function as presentations. They are mapped by the translation machinery onto 20 amino acids plus one stop signal, giving 21 distinct meanings. Many codons are synonymous: they code for the same amino acid. Synonymous codons therefore stand in the relation of admissible equivalence; they are distinct presentations of the same output identity.

After quotienting the 64 codons by their translated meanings, the synonymous adjacencies become transformations that change the presentation without changing the meaning. Single-nucleotide changes correspond to local moves in the presentation space. Certain orderings of the nucleotides (notably G-A-C-U and its reverse) maximize the number of identity-preserving nearest-neighbor connections. These orderings extremize a simple equivalence action that rewards local preservation of meaning under elementary transformations.

The model demonstrates, in a purely combinatorial setting, how many presentations can collapse into fewer stable meanings while retaining nontrivial adjacency, redundancy, and topology. It shows that preferred geometries can emerge from the requirement of maximal local coherence. The same requirement, transferred to the physical setting, suggests that the relational structures realized in nature may be those that most efficiently preserve coherent identity under elementary transport and deformation. The genetic-code example is not offered as evidence that fundamental physics is biological; it is offered as a compact, fully explicit toy universe in which the distinction between presentation and meaning, and the consequences of that distinction, can be studied directly.

12.4 Computational research program, criteria for success, and staged development path

The framework is advanced as a research program rather than a completed theory. Its further development requires concrete computational and mathematical work. Finite equivalence

networks, simplicial and cubical complexes, and higher-categorical models can be constructed and evolved numerically to test whether locality, dimension, causal cones, curvature, and stable defects emerge from simple rules of coherent transport. Toy cosmologies built from evolving equivalence networks can be used to study the appearance of metric and causal structure. Quantum simulation can be performed by summing amplitudes over finite groupoids and comparing the results with conventional Hilbert-space calculations.

Success is measured by several criteria. The framework must recover established low-energy physics, including gauge theory, general relativity, and quantum mechanics, as effective or truncated descriptions. It must be mathematically consistent and must eventually yield novel, falsifiable predictions that distinguish it from existing formulations. It must clarify the origin of probabilities, the emergence of classical outcomes, and the status of background independence. A staged strategy proceeds from finite relational models, through emergent metric and particle-like structures, to quantum amplitudes, and finally to gravitational and cosmological applications.

The central question of physics is thereby shifted. Instead of asking what fundamental states exist, one asks which transformations permit different presentations to count as the same reality and what physical structures arise when those transformations compose coherently or fail to do so. The answer, according to the program developed here, is that reality is constituted by equivalence among presentations, that geometry and matter emerge from the cost and consistency of transporting that equivalence, and that quantum and thermodynamic phenomena reflect the higher structure and truncation of the resulting relational web.

Postscript

The shift proposed in this paper can be illustrated with a simple analogy. The pieces in a LEGO set are not fundamental, self-contained building blocks whose combinations are secondary. Rather, each piece only acquires stable physical identity through the coherent ways it can connect to other pieces. What a piece *is*—its effective existence and persistence—is constituted by the admissible transformations and constructions it can participate in without breaking the overall structure.

In the same spirit, this framework suggests that physical entities are not primarily states or substances occupying locations in a pre-given space. They are coherent patterns within a web of relations. Presentations remain useful as local descriptions, but their identity and persistence arise from the equivalences that allow them to be transported, compared, and recognized across changing contexts. Geometry, matter, and quantum behavior then appear as different manifestations of how these relations can be coherently maintained or obstructed.

The LEGO analogy is imperfect, as all analogies are. A single brick can still be held in one's hand. Yet the point remains: its significance as part of a physical world depends on the structured possibilities of connection. The same may be true of reality itself. What something *is* may ultimately depend less on what it contains in isolation and more on the admissible ways it can relate to everything else while remaining itself.

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